ONE-DIMENSIONAL SIMULATION OF TWO STROKE HYDROGEN DIRECT INJECTION LINEAR GENERATOR FREE-PISTON ENGINE

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We certify that the project entitled "One-dimensional simulation of two stroke hydrogen direct injection linear generator free-piston engine" is written by Muhammad Alliff bin Rahim. We have examined the final copy of this project and in our opinion; it is fully adequate in terms of scope and quality for the award of the degree of Bachelor of Engineering. We herewith recommend that it be accepted in partial fulfillment of the requirements for the degree of Bachelor of Mechanical Engineering with Automotive.

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SUPERVISOR'S DECLARATION

I hereby declare that I have checked this project report and in my opinion this project is satisfactory in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering with Automotive.

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STUDENT'S DECLARATION

I hereby declare that the work in this report is my own except for quotations and summaries which have been duly acknowledged. The report has not been accepted for any degree and is not concurrently submitted for award of other degree.

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ABSTRACT

Developing one-dimensional (1D) simulation of two stroke hydrogen direct injection linear generator free-piston engine (2-stroke H_2-DI LGFPE) is a low cost approach and it can avoid errors. A 1D simulation 2-stroke H_2-DI LGFPE has been developed using GT-POWER software. The performance parameters of a 2-stroke H_2-DI LGFPE have been investigated through various bore and stroke configurations. The performance parameter is also obtained by identifying 2-stroke H_2-DI LGFPE at various start of fuel injection (SOF), start of ignition (SOI) and fuel per cycle (FPC). The modeling of 2-stroke H_2-DI LGFPE in GT-POWER requires different technique than the conventional engine since the crank slider mechanism is absent. The results from the simulation are compared with Fathallah, 2009, Maher, 2004 and Mikalsen, 2008c. From the analysis, the optimum performance is obtained when bore-stroke (B/S) ratio is 0.86. For the SOF, the optimum performance gain at piston position of 65.17 mm before TDC (bTDC). The optimum time for SOI is when piston position at 66.32 bTDC in order to get a better performance of 2-stroke H_2-DI LGFPE. The operation at high engine speed of 6000 RPM, the optimum performance gains at FPC 100 mg which is a rich operation for 2-stroke H_2-DI LGFPE simulated. At engine speed within the range of 1000 RPM until 4000 RPM, lean operation should be chosen in order to reduce brake specific fuel consumption (BSFC). However, the lean operation will result in reducing the brake power of the LGFPE.

ABSTRAK

Simulasi satu dimensi (1D) enjin dua lejang hidrogen suntikan terus penjana lelurus omboh bebas (2-stroke H_2-DI LGFPE) adalah sebuah pendekatan kos rendah dan dapat mengelakkan ralat. Sebuah 1D simulasi 2-stroke H_2-DI LGFPE telah dibangunkan menggunakan perisian GT-POWER. Parameter prestasi suatu 2-stroke H_2-DI LGFPE telah dikaji selidik melalui pelbagai saiz diameter silinder dan lejang. Parameter prestasi juga diperoleh dengan mengenalpasti 2-stroke H_2-DI LGFPE pelbagai di permulaan mengisi bahan bakar (SOF), permulaan pembakaran (SOI) dan bahan bakar per kitaran (FPC). Pemodelan 2-stroke H_2-DI LGFPE di GT-POWER memerlukan teknik yang berbeza dari mesin konvensional kerana ketiadaan aci engkol. Hasil dari simulasi dibandingkan dengan Fathallah, 2009, Maher, 2004 dan Mikalsen, 2008c. Dari hasil analisis tersebut, prestasi optimum diperoleh pada nisbah dimeter silinder dan lejang (B/S) 0.86. Untuk SOF, prestasi yang optimum pada kedudukan diperoleh pada kedudukan omboh 65.17 mm sebelum takat paling atas (bTDC). Waktu optimum untuk SOI adalah ketika posisi omboh 66.32 bTDC untuk mendapatkan prestasi yang lebih baik untuk 2-stroke H_2-DI LGFPE. Untuk operasi pada kelajuan enjin 6000 RPM, prestasi optimum diperoleh pada FPC 100 mg yang nisbah udara-bahan bahan adalah rendah berbanding FPC lain untuk 2-stroke H_2-DI LGFPE yang disimulasi. Pada kelajuan enjin 1000 RPM sehingga 4000 RPM, operasi kurang bahan bakar harus dipilih untuk mengurangkan penggunaan bahan bakar khusus (BSFC). Namun, operasi kurang bahan bakar akan mengakibatkan kuasa brek LGFPE berkurangan.

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LIST OF SYMBOLS

A_p	Cross section area of cylinder
N	Engine Speed
P	Pressure
Q_{HV}	Heating value of fuel
T	Temperature
$\overline{U}_p$	Average piston speed
V	Cylinder volume
V_c	Clearance volume
V_d	Displacement volume
W	Work
$\dot{W}$	Power
$\dot{W}_b$	Brake power
$\dot{W}_f$	Friction power
$\dot{W}_i$	Indicated power
c_v	Specific heat at constant volume
k	Ratio of specific heat
m_f	Mass of fuel
m_m	Mass of gas mixture
mep	Mean effective pressure
n	Number of revolutions per cycle
q	Heat transfer per unit mass
r_c	Compression ratio
v	Specific volume
w	Specific work
η_c	Combustion efficiency
η_m	Mechanical efficiency
λ	Lamda value

LIST OF ABBREVIATIONS

AFR	Air-fuel ratio
aTDC	After top dead center
bTDC	Before top dead center
BDC	Bottom dead center
BSFC	Brake specific fuel consumption
CAD	Crank angle degree
CO_2	Carbon dioxide
DI	Direct injection
FPC	Fuel per cycle
FPE	Free-piston engine
HCCI	Homogeneous charge compression ignition
H_2	Hydrogen
LGFPE	Linear generator free-piston engine
NO_x	Nitrogen oxide
SI	Spark ignition
SOF	Start of fuel injection
SOI	Start of ignition
TDC	Top dead center
1D	1-dimensional

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

Nowadays, the use of fossil fuel is increasing and the emission of carbon dioxide (CO_2) is hurting the environment. It is illustrated in Figure 1.1 that vehicles lead to significant amount of carbon dioxide emission and other pollutions. The Figure 1.1 shows that the emission of pollution caused by fossil fuel is increasing from 1850 until 2009. The emission of CO_2 and pollutions brings to the development of a more environmental friendly fuel chains and the development of hybrid vehicles that stands out as a promising technology for the future.

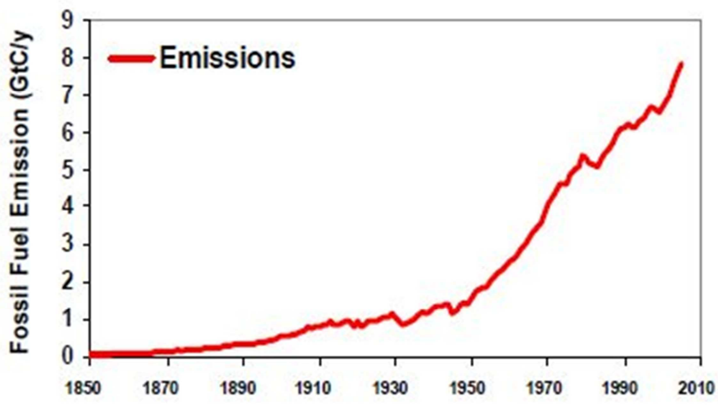

Figure 1.1: Global carbon emissions from fossil fuels.

Source: Climate Progress and Climate Feedback 2008

Besides, rising of global fossil fuel prices also leads to significant research on hybrid vehicle which will reduce the reliability on fossil fuels. Furthermore, power also degrades as a result of the high friction in conventional engine. Hence, these problems have put the research and development of free-piston engine to intensity.

Free-piston engines are characterized by a purely linear piston motion that is not restricted by a crank mechanism (Mikalsen, 2007a). The interaction of the components of the free-piston engines are coupled, through a “free” piston which is a significant feature for the engine. The absence of kinematic constraints has made the piston to be “free” where the piston motion will result in an imbalance of forces acting on the piston (Aichlmayr, 2002). Unlike conventional engine which uses the rotation motion and more complex component that causes the high friction and resulting less engine efficiency, free-piston engine uses the linear motion and fewer components that improve engine efficiency and reduce friction as stated by Mikalsen, 2009a, Xiao, 2008 and Mikalsen, 2008a. Several designs of free-piston engine concept have been proposed. Generally, there are four types of free-piston engine applications which are free-piston air compressor, free-piston gas generator, free-piston hydraulic pump and free-piston engine generator (Aichlmayr, 2002).

The free-piston engine generator consists of free-piston coupled to a linear electric machine. Figure 1.2 illustrates the free-piston engine generator prototype configurations.

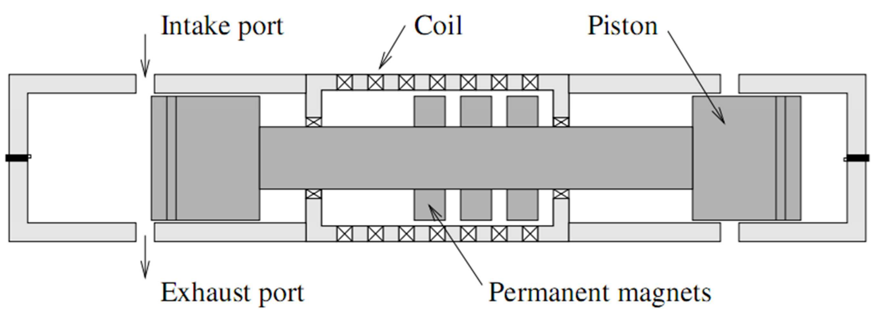

Figure 1.2: Illustration of the free-piston engine generator prototype configurations.

Source: Nandkumar 1998

There are many advantages of a free-piston linear generator engine (LGFPE) compared to conventional engines such as high power to weight ratio, multi-fuel capability and low manufacturing cost and low maintenance due to less components and mechanical simplicity (Razali, 2008).

Throughout this thesis, the simulation of two-stroke hydrogen direct injection free-piston linear generator engine prototype using GT-Power will be developed. The importance of this project is to improve the performance of LPGE.

1.2 PROBLEM STATEMENT

Conventional engines used the rotation motion and have more complex component that causes high frictions resulting in less engine efficiency. Compared to the LGFPE where it uses the linear motion and has fewer components that improve engine efficiency and reduces friction. Developing LGFPE can either be done by real prototype of the engine or through design and simulation by using GT-POWER. The downside of developing a real engine is that it is costly and more error prone compared to the simulation by using GT-POWER. By using GT-POWER, various configurations of bore and stroke are needed to investigate and to get the optimum performance of the LGFPE. Besides, it is required to identify the optimum time for start of fuel injection (SOF), start of ignition (SOI) and mass of fuel per cycle (FPC) in order to obtain optimum performance parameters.

1.3 OBJECTIVES OF THE PROJECT

The objectives of this research are:

1. To develop 1-Dimensional model of two-stroke hydrogen direct injection linear generator free-piston engine using GT-POWER.
2. To investigate the two-stroke hydrogen direct injection linear generator free-piston engine performance for various bore and stroke configurations.

3. To obtain performance parameters identifying two-stroke hydrogen direct injection linear generator free-piston engine at various setting of start of fuel injection, start of ignition and fuel per cycle.

1.4 SCOPE OF STUDY

The scopes of this project are:

1. The system of free-piston two-stroke hydrogen direct injection linear generator free-piston engine is developed by using GT-POWER software.
2. Limited to the two-stroke hydrogen direct injection linear generator free-piston engine specifications as reported by Razali, 2008.
3. P-V diagram, in-cylinder pressure, brake power from 1000 RPM to 6000 RPM and BSFC from 1000 RPM to 6000 RPM are the performance parameters investigated at no load condition.

1.5 SUMMARY

Chapter 1 has discussed briefly about project background, problem statement, objective and scope of the project on developing a two-stroke hydrogen direct injection free-piston linear generator by using GT-POWER software for different performance parameters at various bore and stroke configurations, SOF, SOI and FPC. This chapter is a fundamental for the project and act as a guideline for project research completion.

CHAPTER 2

LITERATURE REVIEW

2.1 TWO-STROKE ENGINE

Four-stroke cycle creates only one power stroke every two revolutions. This leads to a cycle giving one power stroke per revolution. The solution is to exhaust the cylinder as the piston approached and passed the bottom, or outer, dead center, and to use the depression caused by the inertia of the high speed flow of the outgoing gases to assist the induction process. The induction process must be timed to begin shortly before the exhaust ports close and to continue for a brief period during the subsequent upstroke of the piston. The objective is to complete both induction and exhaust within the period that the piston was swinging over BDC, and that will result to a small amount of detraction from the exhaust or compression strokes. This is not too difficult because the piston dwells momentarily at BDC, from 45° before to 45° after represents less than one-eighth of its displacement from the bottom end of its stroke (Garrett, 2001). In a two-stroke engine, the burnt gas is exhausted from the cylinder primarily by the pressure difference between it and atmosphere, rather than by the motion of the piston.

The two-stroke cycle, starting at top, or inner, dead center firing stroke, compromises first the combined power and exhaust stroke as the piston moves down, and then the induction and compression as it moves up again. A slight over-simplification has made the function at BDC to overlap. Doubling the number of power strokes per revolution does not offer more potential for a power output double that of the four-stroke engine. The outputs of two-stroke engines range from only about 10 to 40% above those of equivalent four-stroke units that will result in the pumping losses in the two-stroke engine becomes generally higher (Garrett, 2001). It is not possible to develop such high mean effective pressure as with the two-stroke cycle because both induction and exhaust occur around BDC, the inlet and exhaust ports cab be situated near the bottom end of the cylinder and can be covered and uncovered by the piston. This obviates the need for valves and their actuating gear, so one of the major attractions of a two-stroke engine of this layout is its extreme simplicity, and therefore low cost (Garrett, 2001).

It also, however, leads to one of its principal disadvantages, which is that its fuel consumption is high because over most, if not all, of its speed range some of the incoming charge inevitably is lost through the exhaust ports during the overlap period. Although both efficiency and specific power output can be improve by measures such as injection of the fuel after the exhaust port are closed, incorporating poppet type exhaust valves into the head, scavenging the exhaust gases more effectively by supercharging or even incorporating extra cylinders for scavenging by providing extra air, all involve in the increment of the complexity of the engine, which reduces its attractiveness relative to a four-stroke unit (Garrett, 2001). The advantages of the two-stroke consists of mechanical simplicity, low cost, mechanical silence, smooth torque owing to the shortness of the interval between combustion impulses, and consequently the mall flywheel and light weighted. If it is valid, it would still have to be set against the apparently inescapable disadvantages which is greater noise due to the sudden uncovering of the ports by the pistons, high specific fuel consumption, excessive hydrocarbon content of the exhaust gas, difficulty of starting and irregular firing at idling and light load with some types of two-stroke engine (Garrett, 2001).

2.2 DIRECT INJECTION SYSTEM FOR SI ENGINE

Injection of fuel is done during the compression stroke and is similar to fuel injection in a CI engine. Because of the very short time available for vaporization and mixing with air, very fine droplets of fuel are required, as are high turbulence and bulk mass motion within the combustion chamber. The injector pressure must be higher than the pressure required for port injection. This is the result of the high pressure into which the fuel is being injected, and because if the requirement for finer droplets of fuel. There are two stages of injection which is a pilot injection for ignition followed by the main injection. Injection of air with fuel will vaporize and mixed time can be greatly reduced. This method also makes possible the stratification of the air-fuel mixture, which is the way these engines operate. In stratified charge combustion, a rich mixture is established around the sparkplug, while a very lean mixture fills the rest of the combustion chamber. Overall fuel ratio as high of 50:1 will not ignite if it were homogeneous. By operating with a very lean mixture combustion temperature is reduced, and this reduces heat loss which will give higher thermal efficiency (Pulkrabek, 1997).

The fuel-rich mixture near the sparkplug readily ignites and burns with a fast flame speed. After that, the ignition of the lean mixture in the rest of the combustion chamber occurs. As stated by Pulkrabek, 1997, to establish this stratified air-fuel distribution, a sequence of injections is required;

i. Some fuel is injected very early, during the intake stroke. This establishes the lean homogenous mixture that fills the combustion chamber. Only low injection pressure is required.
ii. During the compression stroke additional fuel is injected at very high pressure to create the rich fuel-air mixture near the sparkplug. Pressures can be as high as 10 MPa or greater, which much higher pressures being tested in experimental development work.
iii. The sparkplug is spark for ignition.

2.3 HOMOGENOUS AND STRATIFIED COMBUSTION

This stratified charge consists of a region of fuel-rich mixture and pure air or a mixture of air and recycled burnt gases in the remaining volume that is shown if the Figure 2.1. This stratified charge is achieved by a late injection during the compression stroke. The combustion and energy release only take part inside the mixture region. A further advantage of the DI process due to stratification where the reactive zone is separated from the wall by the non-reacting part of the cylinder charge and the heat losses to the engine walls will be reduced (Baumgarten, 2005).

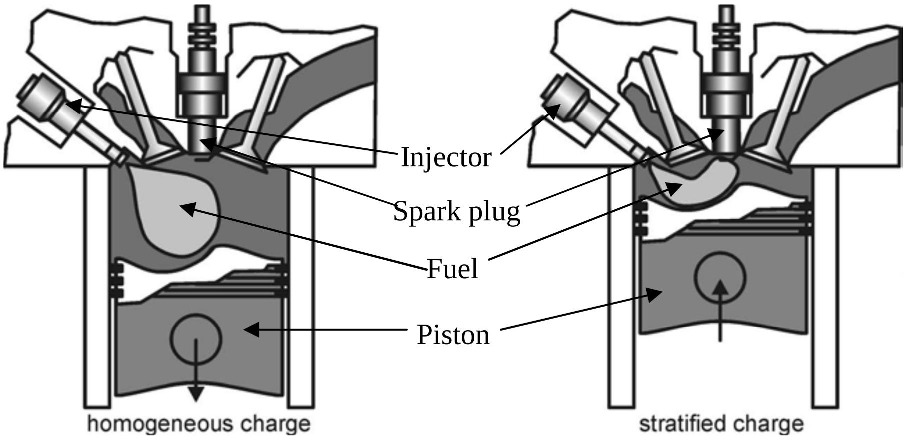

Figure 2.1: Homogenous (early injection) and stratified-charge mode (late injection)

Source: Baumgarten 2006

The main advantage of the direct injection is the fact that in the case of part load throttling can be eliminated and thus pumping losses are minimized as illustrated in Figure 2.2. The reduction of load can be achieved by reduction of the injected fuel quantity, while the airflow is not throttled. This approach of qualitative load control is well known from the DI diesel engine (Baumgarten, 2006). There is no homogenous fuel-air mixture inside the whole cylinder; instead there will be a stratified charge.

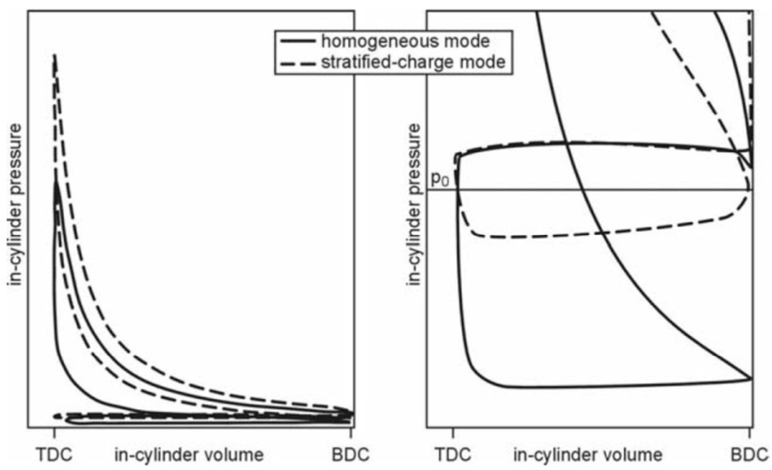

Figure 2.2: Reduction of throttle losses, stratified-charge combustion

Source: Baumgarten 2006

2.4 HYDROGEN FUEL

Hydrogen is important nowadays and it is projected as a possible major fuel of the future to replace the eventual declining gasoline supplies. The combustion process in conventional engines, the fuel intake is on the opposite side of the engine from where combustion occurs, lowering the chance of pre-ignition from a hot engine block; hydrogen fuel ignites very easily (Pulkrabek, 1997).

Hydrogen fuel in gaseous state is known to have ability in creating quality mixture both outside and inside of the cylinder, wide flammability, a high calorific value and high anti-knock properties. This will result in high compression ratio engine and high thermal efficiency. Table 2.1 shows the general properties of hydrogen as reported by Maher, 2004 and Verhelst, 2009.

Table 2.1: General properties of hydrogen.

Fuel	Hydrogen
Molecular weight	2
Heating value	120MJ/kg
Stoichiometric air-fuel ratio $(AF)_s$	34.3
Auto-ignition temperature	580 °C
Ignition energy in air for stoichiometric mixture	0.02
Laminar burning velocity in air (at stoichiometric)	275 cm/s
Flammability limits (λ)	10-0.14

Source: Maher 2004

As reported by Pulkrabek, 1997, hydrogen fuel has its advantages and disadvantages that must be taken in consideration. The main advantage is hydrogen fuel has high octane number because when used at a fuel equivalence ratio of 0.6, compression ratios of about 14:1 can be utilized without serious knock problems. Other than that, hydrogen fuel has low emission of NO_x when the engine is operated at low fuel equivalence ratio. The fuel availability is high because there are a number of different ways of obtaining hydrogen which includes natural gas resources and electrolysis of water. The hydrogen fuel is also environmental friendly because fuel leakage of the hydrogen fuel does not harm the environment.